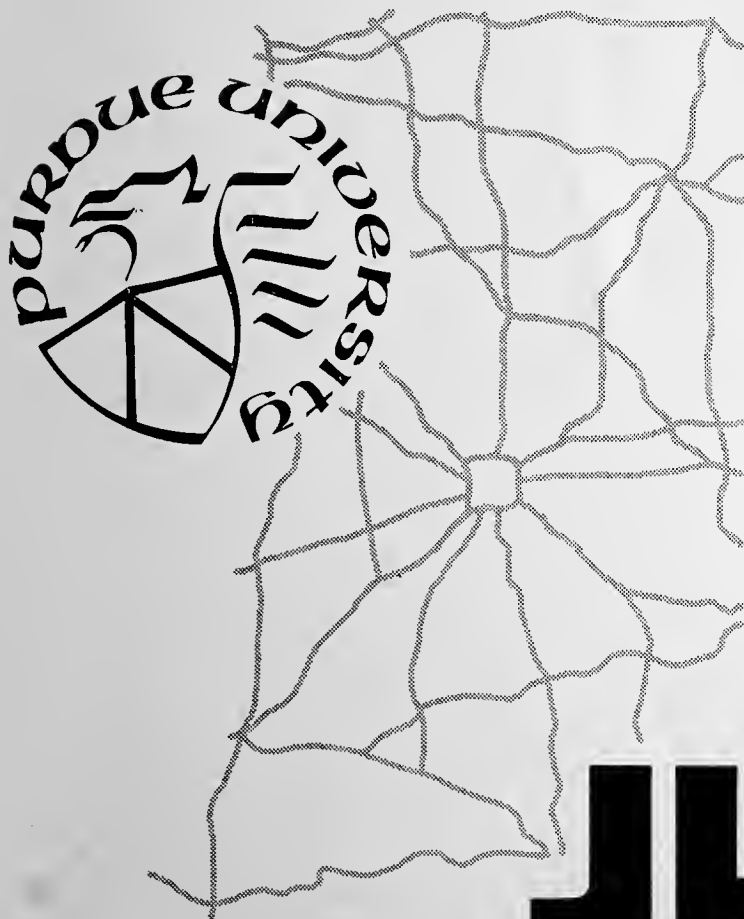


USE OF SHALE IN EMBANKMENTS

AUGUST 1973 — NUMBER 14



BY

P. DEO

L. E. WOOD

C. W. LOVELL, JR.

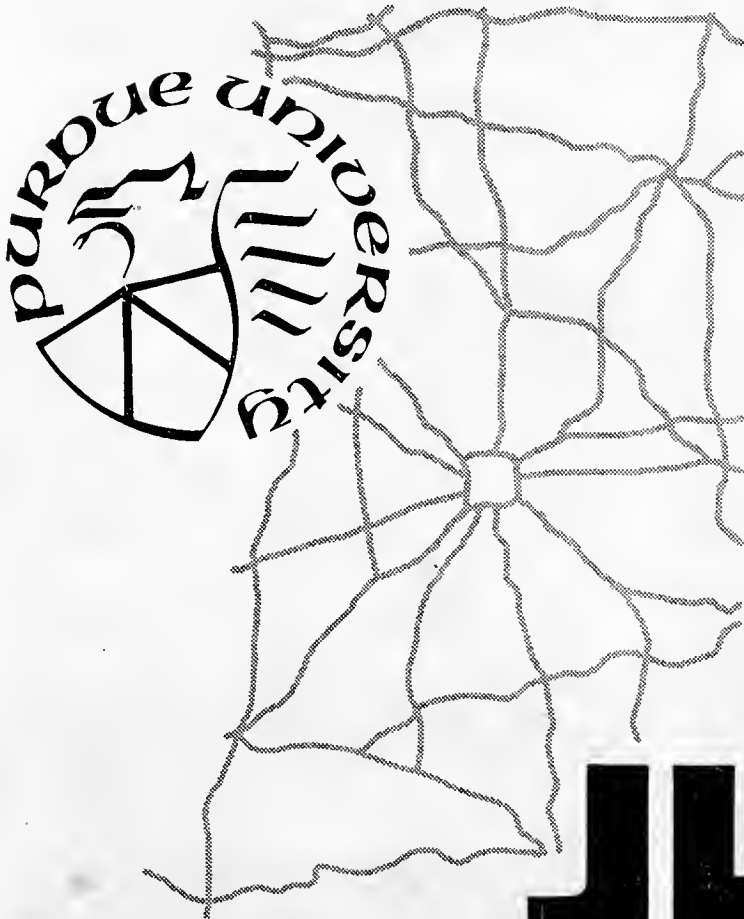
JHRP

JOINT HIGHWAY RESEARCH PROJECT

PURDUE UNIVERSITY AND
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Technical Paper
USE OF SHALE IN EMBANKMENTS

TO: J. F. McLaughlin, Director
Joint Highway Research Project

August 29, 1973

FROM: H. L. Michael, Associate Director
Joint Highway Research Project

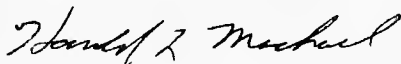
Project: C-36-5J

File: 6-6-10

The attached Technical Paper "Use of Shale in Embankments" has been authored by Messrs. P. Deo, L. E. Wood and C. W. Lovell, Jr., former or present members of our staff. The paper is from the research conducted by Mr. Deo, directed by Professors Wood and Lovell and reported in J.H.R.P. Report No. 45, 1972, titled "Shales as Embankment Materials".

The paper will be presented at the Summer Meeting of the Highway Research Board to be held in Olympia, Washington in early August 1973. It is presented to the Board for approval of publication as it is planned for such action by the Highway Research Board.

Respectfully submitted,



Harold L. Michael
Associate Director

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Technical Paper
USE OF SHALE IN EMBANKMENTS

by

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Project No.: C-36-5J

File No.: 6-6-10

Conducted by

Joint Highway Research Project
Engineering Experiment Station
Purdue University

In Cooperation With
Indiana State Highway Commission

Purdue University
West Lafayette, Indiana
August 1973

USE OF SHALE IN EMBANKMENTS

ABSTRACT

Guidelines for the design and construction of soil embankments are sufficiently developed so that unsatisfactory performance by these fills is relatively rare. The same is true for rock fills, where the sound and durable rock is placed in large chunks, and with large voids between the chunks. However, there are transition materials or "soft rocks" for which placement in large chunks may lead to highly unsatisfactory embankment performance. Shales afford the prominent example, since the large pieces may degrade (slake) into soil in service. This soil may in turn sift down into the large voids, with the net result that large settlements, and even slope instability, may occur. Embankment failure due to the above mentioned circumstances resulted in closing lanes on Interstate 74 in Indiana and required costly repairs. Similar failures have occurred in other states in the midwest.

The harder and more durable shales can probably be placed as rock fills with certain safeguards. The shales of very low durability must be thoroughly degraded at the end of compaction, i.e., must be treated as soil fills. A full spectrum of durabilities exists between these limits. The engineer obviously needs a classification system which will establish where, in the possible range of relative durabilities, a potential embankment shale lies.

To develop such a classification for Indiana shales, materials were sampled and subjected to a battery of durability, stability and miscellaneous type tests. The durability tests were those used as standard for mineral aggregates, but modified in severity to account for the "soft rock" being evaluated. It was concluded that the desired classification into four groupings, viz., soil-like, intermediate-1, intermediate-2, and rock-like shales, could be accomplished with no more than four rather simple tests: one cycle slaking in water, slake-durability on an initially dry sample, slake-durability on a soaked sample, and a modified sodium sulfate soundness test.

The paper describes the Indiana shales tested, the tests proper, and the response of the Indiana shales in the tests. It concludes with a flow chart showing how the tests are used to accomplish the shale classification.

USE OF SHALE IN EMBANKMENTS

INTRODUCTION

Highways embankments are commonly built with soil, and less commonly with rock. However in either case, design standards and construction specifications are backed with sufficient experience to be applied with confidence. But how about the family of constructional materials which is transitional between soil and rock, viz., the "soft rocks".

Soft rocks include all types of mudrock, which is any sedimentary rock containing at least 50% silt and clay constituents. Mudrock is thus a general name for all varieties of siltrocks, clayrocks, mudstones, siltstones, mudshales, silt shales, clay shales and argillites. Twenhofel (14)¹, Underwood (15), Ingram (9), and Gamble (6) have differentiated among these rocks. Figure 1 is an example. This paper concentrates on the shales.

When shales are used as embankment materials in the central U.S., the engineer tends to view them with suspicion, and often recommends design and construction procedures which are conservative, e.g., extra rolling to fragment the material, placing another material between the shale and the atmosphere (encasement), flattening slopes, special attention to surface and subsurface drainage, and using berms. These procedures have reduced, but not eliminated, instabilities of shale embankments (8, 12, 16). However, it is probable that the current practice is generally too conservative, e.g., some relatively high quality shales are being unnecessarily degraded and placed as soil fill.

1. Items in parentheses refer to entries in the Bibliography.

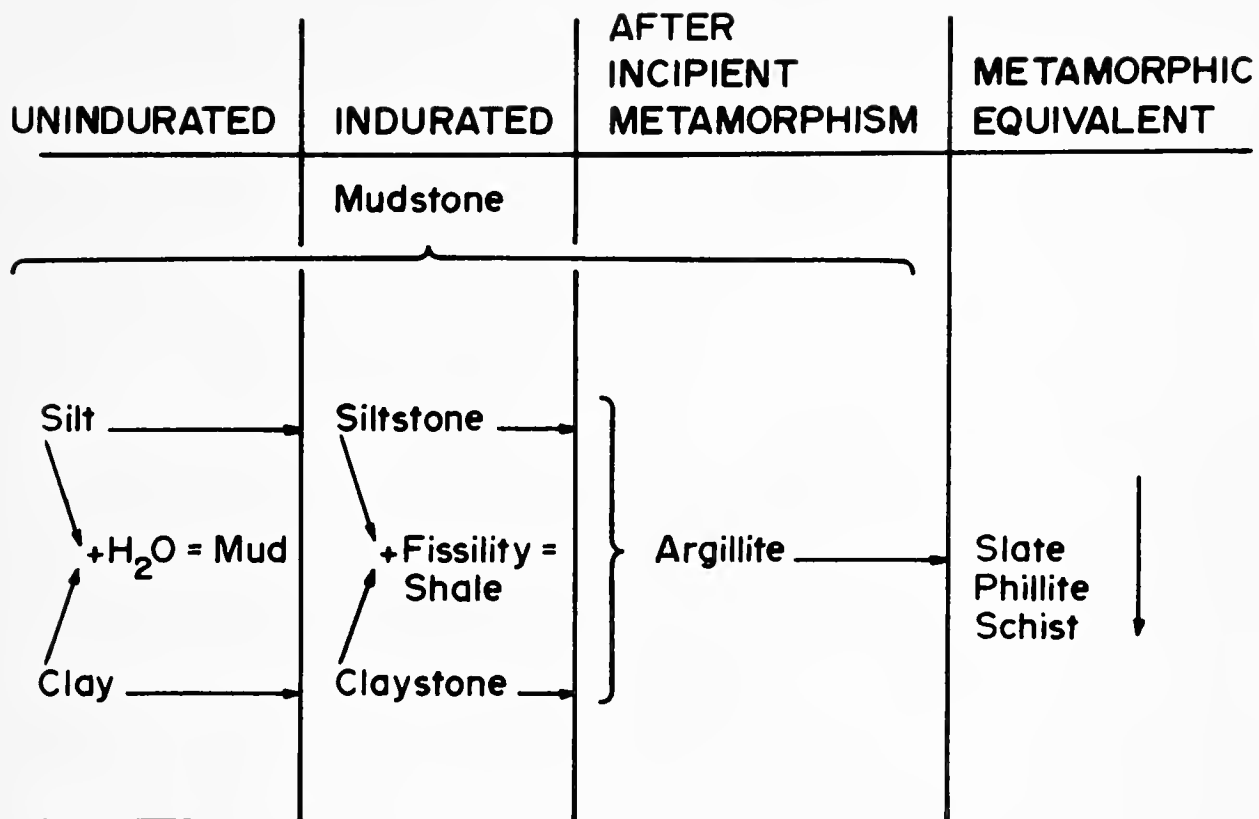


FIGURE 1 - CLASSIFICATION OF SHALE AND RELATED ROCKS (14).

It is suggested that shales can be grouped in the following four categories.

1. Shales which are highly susceptible to post-constructional degradation and when so reduced are actually inferior in performance to normal fine grained soils. The use of these materials in embankments should be restricted.

2. Shales which are about "at par" with normal fine grained soils and may be used with common soil design and construction controls, if they are rather thoroughly degraded in the construction process.

3. Shales which are imperfectly degraded in the construction process, and which will be only slightly degraded in service, are stronger than soils, yet cannot be placed as rockfill.

4. Shales which are very difficult to degrade can likely be placed as rockfills. These materials are intrinsically superior to soil in fills if certain construction problems can be overcome.

This paper reviews the current placement technology for shale embankments and suggests a simple and inexpensive testing program to classify the shales with respect to their use in embankments.

PROBLEMS WITH SHALES AS EMBANKMENT MATERIALS

Potential problems within an embankment constructed with shales include:

- a. Settlement due to loading, drying, slaking¹, or thawing.

1. Slaking is the process through which a material disintegrates or crumbles into small particulate units when exposed to moisture, and especially when dried and immersed in water.

- b. Heave caused by wetting or freezing.
- c. Slope instability.
- d. Surface and subsurface erosion.

The degree to which soft rocks will demonstrate poor performance depends largely on their service environment, both man-made and natural. For example, unless the material becomes significantly wetter than the placement condition, slaking may not occur. Once exposed to increased moisture, slaking may occur quickly, in many years, or not at all. The practical consequence of the slaking, if it occurs, depends primarily upon the relative abundance of large voids in the compacted mass, into which the slaked material can settle. The size and frequency of large voids is rather directly related, in turn, to the relative abundance of large chunks of shale in the embankment. If large chunks of slaking materials are placed in the embankment, major problems can be anticipated. If on the other hand, the slaking material is reduced to small pieces in the construction process, the subsequent slaking in service may produce no unacceptable densifications or surface displacements.

Degradation of material in the embankment can be controlled by effective drainage and/or proper encasement of the embankments. Even relatively nonslaking materials are weakened and made more compressible by increased moisture. Other shales contain enough expansive minerals to cause significant swelling upon wetting and shrinkage upon drying, with potentially harmful effects on the embankment and/or the overlying pavement.

If one is able to assess the general susceptibility of a material to slaking, volume change, and the like, in the projected service

environment, more rational decisions can be reached in the design and construction processes, thereby increasing the probability that satisfactory service will be produced with economy.

CURRENT PLACEMENT TECHNOLOGY

Shales have been treated sometimes as a soil, sometimes as a rock in embankments. Sherard and others (12) emphasize the importance of proper investigation of these materials and handling each as an individual problem. Test embankment sections are recommended, where possible.

The various agencies constructing embankments have separate specifications for soils and rocks. However, there may be no fixed specifications for shale or other soft rocks embankments. The Indiana State Highway Commission uses shales in embankments with the following provisions:

1. Shales are subjected to thorough breakdown in the process of excavation, hauling, placement and compaction; in other words, treated like soil fill. Occasionally, lift thicknesses are made even thinner than for soil.

2. A non-shale soil encasement of two or three feet is provided on all boundaries of the embankment.

3. The shale-soil mixture, when treated in the specified manner, is considered to be highly competent, and no other special design features are needed.

Such provisions are normally contained in a special construction specification statement, and are often quite qualitative.

Some agencies, including the Soil Conservation Service in Indiana, use shale in the construction of small dams (13). Durable and non-durable (soil-like) shales are recognized, but there are no quantitative criteria to indicate into which group the shale in question should fall. In Indiana the SCS has used shales with the following provisions:

Durable Shales. 1. The maximum size of rock fragments used is eighteen inches, provided that such fragments are completely embedded in a matrix of compacted fill.

2. The maximum thickness of rock layers before compaction is twenty-four inches.

3. Broken shale and limestone mixtures may be used in rock fill.

4. Rock fill has a cover of weathering resistant material of two to four feet.

5. A minimum compacted dry unit weight of 112.5 pcf was used for two different shales. This number could vary for other shales (13).

Soil-like Shales. 1. A shale which completely slakes in water in a few (about ten) minutes can also be used in embankment provided it is thoroughly broken down to soil during excavation, hauling, placement, and compaction.

2. A minimum encasement of four feet of non-shale soil is needed.

3. The unit weight of the fill should be at least 95 percent of the maximum determined by ASTM D 698-66T, Moisture-Density Relations of Soils (3).

With the current state of the art in the midwestern U.S., a considerable amount of judgment may be required at the time of construction, and there is a definite potential for being unduly conservative, and even

occasionally, erring on the unsafe side.

ENGINEERING CLASSIFICATION OF SHALES

There is a need in the midwest to develop a simple and inexpensive testing routine to classify shales with respect to their suitability for use in embankments. With this objective, representative samples of shales were collected from fifteen different locations within the state of Indiana, see Figure 2. These materials covered a wide behavioral spectrum, from very hard and durable ones to those which rapidly weather into soil.

The testing which was conducted in the laboratory can be grouped into four categories.

a) Degradation Type Tests measured slaking and other breakdown of the material. As the standard tests were inappropriate for soft rocks, it was necessary to develop new ones, or at least to modify existing ones. This group includes different types of slaking tests (in air, water, and sodium sulfate solution) and abrasion tests.

b) Soil-Type Standard Identification Tests were conducted on the shales in a thoroughly degraded condition. This group included Atterberg limits, grain size distribution and X-ray diffraction.

c) Compaction and Load-Deformation Tests, principally California Bearing Ratios, were performed on as-compacted and soaked samples.

d) Miscellaneous Type Tests were performed which included: 1) absorption-time, 2) bulk density, and 3) certain breaking characteristics of the materials.

All the tests did not yield useful descriptors for classifying the shale for embankments. Accordingly, only certain of them were selected

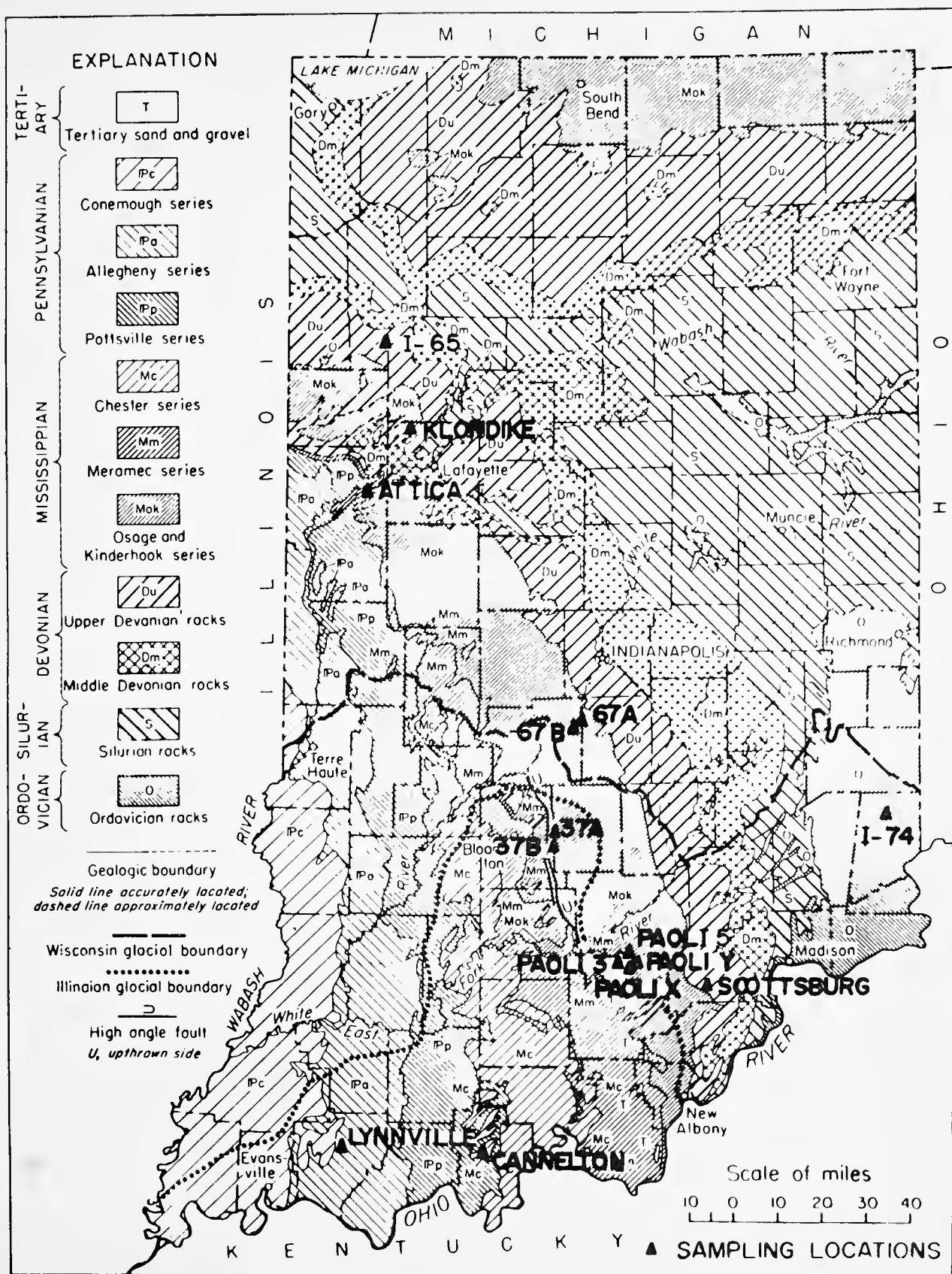


FIGURE 2. BEDROCK GEOLOGY OF INDIANA, AND SHALE SAMPLING LOCATIONS

for use in the recommended classification system. The procedures for those tests which yielded useful results are described in Appendix A.

TEST RESULTS AND DISCUSSION

Simple Slaking Tests

On the basis of three tests, viz., slaking in air, slaking in water in one cycle, and slaking in water in five cycles, all the sampled shales could be classified into three groups. (See Figure 2.)

1. Shales which are severely affected by water, i.e., slake significantly. Only Cannelton, I-74, and Paoli Y are in this category.
2. Shales which are affected by water to a very minor extent during five cycles. Paoli X and I-65 are in this category.
3. Shales which appear totally unaffected by five cycles. Paoli 3, Paoli 5, Lynnville, Attica, 67A, 67B, 37A, 37B, Scottsburg, and Klondike fall in this category.

Those shales which slake significantly in the five cycle test should certainly be viewed as non-durable. If used in embankment, they should be accorded very special treatment. Groups 2 and 3 perform satisfactorily in these tests, but further examination of their characteristics should be undertaken before specifying design and construction details.

Slake Durability Tests

The values of slake durability index for dry samples $(I_d)_d$ and for soaked samples $(I_d)_s$ are shown in Table 1. An examination of the values reveals the following points.

TABLE 1. VALUES OF SLAKE DURABILITY INDEX FOR DIFFERENT SAMPLES .

Sample	Slake Durability Index Dry Sample, $(I_d)_d$	Slake Durability Index Soaked Sample, $(I_d)_s$
Cannelton	24.0	0.0
I-74	63.0	24.5
Paoli Y	86.1	56.2
Paoli X	88.8	68.7
Paoli 5	93.8	89.1
Lynnville	93.8	87.2
I-65	93.2	78.5
67B	93.8	90.1
67A	94.9	90.3
Paoli 3	94.5	91.0
Scottsburg	94.0	91.1
37A	94.8	93.6
Klondike	94.2	91.2
Attica	95.0	93.5
37B	95.0	93.6

1. For the shales which completely or partially slake in water, the slake durability index for dry samples also predicts a severe degradation in water. This is true for the Cannelton and I-7⁴ shales.

2. For the shales which have an $(I_d)_d > 85$, the $(I_d)_s$ is probably a better measure. If the $(I_d)_s$ is between 0 and 50, the material is highly susceptible to breakdown in water. An $(I_d)_s$ between 50 and 70 represents an intermediate susceptibility to water. Values between 70 and 90 represent materials with fair to good relative durability.

3. For shales with $(I_d)_s$ values greater than 90 (or perhaps even 85), the test does not distinguish sufficiently among the materials, and other tests are needed if such distinction is desired.

Modified Soundness Test

The results of this test, which seems more effective than others in distinguishing among the harder and more durable shales, are shown in Table 2. The values of soundness index (I_s) range from 0 to 97.2. As this number refers to the percent weight retained on the 5/16 in. sieve at the conclusion of the test, higher values of I_s refer to more durable shales. When this test was run on a sound, medium grained limestone, it gave a soundness index of 99.2.

On the basis of this test, various groupings of materials are suggested:

1. If I_s is less than 20, the material is very susceptible to weathering, and should probably be treated like a fine grained soil.

2. If I_s is between 20 and 50 (perhaps even 70), the material has a relatively high susceptibility to weathering and the material should probably still be treated as a soil.

TABLE 2. RESULTS OF MODIFIED SOUNDNESS TEST .

Sample	Percent Weight Passing 5/16 in. Sieve	Soundness Index, I_s (Percent Weight Retained on 5/16 in. Sieve)
Cannelton	100	0
I-74	100	0
Paoli Y	84	16
Paoli X	69	31
Paoli 5	28	72
Lynnville	14	86
I-65	19	81
67B	17	83
67A	16	84
Paoli 3	16	84
Scottsburg	15	85
37A	5.5	94.5
Klondike	5.4	94.6
Attica	5.2	94.8
37B	2.8	97.2

3a. Materials having values between 90 and 98 are grouped as "Intermediate-1", and are probably little affected by weathering.

3b. Materials having values between 70 and 90 are termed "Intermediate-2". Both intermediate types can be superior to soil as embankment materials, if given adequate treatment in the construction process.

4. If I_g is greater than 98 (no such materials were sampled), the material can probably be treated like a rock.

Compaction and Load-Deformation Tests

Table 3 summarizes the results at optimum moisture content and Standard AASHO effort (2) for all the shales.

The comparisons of the values of as-compacted CBR, soaked CBR, and ratio of soaked CBR to as-compacted CBR show that: as-compacted CBR varied between 2.1 and 31.8, soaked CBR varied between 0.0¹ and 21.8, and the ratio of soaked CBR to as-compacted CBR varied between 0.0 and 0.765. It is noted that for the three materials which show some slaking in water, the values of soaked CBR are 0.0¹, 0.4 and 1.1, while the as-compacted CBR values are 2.1, 6.1 and 8.0. These data imply an extremely weak embankment, should these shales be saturated in service.

The values of soaked CBR varied between 0.0 and 76.5 percent of the as-compacted CBR. As this ratio becomes small, a closer examination of the special provisions for the use of the shale is indicated, e.g., complete compaction degradation, special drainage, and encasement.

1. The breakdown of the surcharged shale sample when soaked was sufficient to produce the 0.0 value. (The authors have not seen a 0.0 CBR value reported previously.)

TABLE 3. RESULTS OF CBR TEST AT STANDARD AASHO EFFORT AND OPTIMUM MOISTURE CONTENT.

Sample	γ_d max pcf	O.M.C. %	CBR as Compacted	CBR Soaked	(CBR Soaked) \div (CBR as compacted), R%	Swell %, S
Cannelton	107.8	14.8	2.1	0.0	0.0	7.8
I-74	117.9	13.8	8.0	1.1	13.7	5.4
Paoli Y	107.4	16.6	6.1	0.4	6.6	5.2
Paoli X	112.2	12.6	12.0	3.3	25.7	2.9
Paoli 5	117.0	10.1	19.9	6.2	31.2	1.0
Lynnville	115.3	8.7	12.4	7.8	63.0	0.6
I-65	117.8	10.2	21.2	8.3	39.2	3.2
67B	119.7	7.5	29.5	15.8	53.6	0.1
67A	119.0	7.3	28.8	15.3	53.5	0.2
Paoli 3	119.2	7.2	28.2	14.7	52.0	0.2
Scottsburg	118.2	6.9	28.4	14.5	51.0	0.0
37A	119.6	8.2	30.2	18.3	60.5	0.0
Klondike	118.3	10.7	23.4	17.2	76.5	0.2
Attica	117.5	7.2	27.4	19.4	71.0	0.0
37B	119.6	7.1	31.8	21.8	68.5	0.0

Swelling Behavior

Swelling after 96 hours of soaking was recorded. The maximum size of shale lumps used was $3/4$ in., and it was thought that a few of the shale pieces might collapse and show a volume decrease upon 96 hours of soaking. However, no such settlement was noted.

For eight of fifteen materials, there was almost no axial swell. At Standard AASHO optimum moisture for the remaining materials, axial swell was 0.6, 1.0, 2.9, 3.2, 5.2, 5.4 and 7.8%. On both sides of optimum moisture content, swell was less than at optimum moisture. Swell also increased with the increase of compaction effort (molding water content constant) and therefore with the increase of dry density. This is similar to fine grained soil results.

An increase in swell is identified with a decrease in CBR ratio. If results are compared for those shales which give a swell of 1.0% or more, there is linear trend for reduction in CBR ratio with the increase of swell.

Breaking Characteristics

Flaky and Flaggy are two characteristic conditions of fissility, and therefore a fissility index or number should be some weighted sum of the two, e.g., a fissility number could be proportional to percent by weight flaky plus a constant times percent by weight flaggy. The flaggy pieces were heavier than flaky pieces when the same amount of breaking effort was applied. Specifically, the weight of flaky pieces varied between 5 and 100 percent of that of the flaggy pieces, and the average weight of flaky pieces was 0.35 times the average weight of flaggy pieces.

TABLE 4. FISSILITY CHARACTERISTICS FOR SHALES.

Sample	% Massive	% Flaggy	% Flaky	Fissility No. (%Flaky + 0.35 %Flaggy)
Cannelton	0	30	70	81
I-74	10	20	70	77
Paoli Y	0	30	70	81
Paoli X	0	50	50	68
Paoli 5	10	40	50	64
Lynnville	20	30	50	61
I-65	0	50	50	68
67B	10	40	50	64
67A	10	40	50	64
Paoli 3	30	40	30	44
Scottsburg	20	40	40	54
37A	30	50	20	38
Klondike	0	50	50	68
Attica	30	60	10	31
37B	30	60	10	31

Therefore, the fissility number was defined as the sum of percent flakiness plus 0.35 times percent flagginess. The values of fissility number for sampled shales ranged between 31 and 68 and are shown in Table 4. The percentage by weight having massive, flaggy and flaky proportions, as determined in the shale breaking characteristics test, is reported in Table 4.

GENERAL DISCUSSION

Several of the degradation type tests may be used to distinguish among the various shales. The soaked durability index and the soundness index seem to be valuable for rating shales as to their relative durability. They apparently reflect a combined effect of various important characteristics of shale, such as, fissility, cementing materials, and amount and type of clay and silt sizes.

Results of compaction and CBR tests on various shales showed a wide range in the values of as-compacted CBR, soaked CBR, the ratio of soaked to as-compacted values, and the peak density on the Standard AASHO compaction curve, i.e., $(\text{CBR})_c$, $(\text{CBR})_s$, R , and $\gamma_{d \text{ max}}$. Higher values of $(\text{CBR})_c$ and $\gamma_{d \text{ max}}$ indicate stronger shales. The value of $(\text{CBR})_s$ is an indicator of both in-service strength and durability, and higher values indicate more strength and durability. Higher values of R predict more durable shales. The results of the CBR tests correlate satisfactorily with soundness index and fissility number.

The use of fissility number seems to be quite promising in categorizing shales. Higher values of fissility number indicate reduced $(\text{CBR})_c$, $(\text{CBR})_s$ and R values. Thus those shales having higher fissility numbers display reduced durability and strength.

On the basis of 4 simple degradation type tests, shales can apparently be classified in the following four groups:

1. Rock like shales
2. Intermediate-1 shales
3. Intermediate-2 shales
4. Soil like shales

The flow chart for classification is shown in Figure 3.

RECOMMENDATIONS AND SUGGESTED CONSTRUCTION PRACTICES

When shale is considered as a construction material in embankments in the midwestern U.S., it should be viewed as a special material, i.e., something between soil and rock. It should be classified in accordance with its probable behavior in the embankment. Before actually specifying use of this type of material, the following steps are recommended.

1. Review the design and construction standards and specifications which would apply if the embankments material were: (a) an average fine grained soil, or (b) an average sedimentary rock, i.e., consider the limits for the real material, which is generally intermediate.

2. Study the proposed fill material to determine whether it is grossly homogeneous or a mixture of unlike materials, e.g., shale and limestone. There are special hazards in the latter case, and extra special attention is required.

3. Perform the slake durability and modified soundness tests. Classify the material in one of the four groups suggested earlier, i.e., Rock like, Intermediate-1, Intermediate-2, or Soil like. (see Figure 3.)

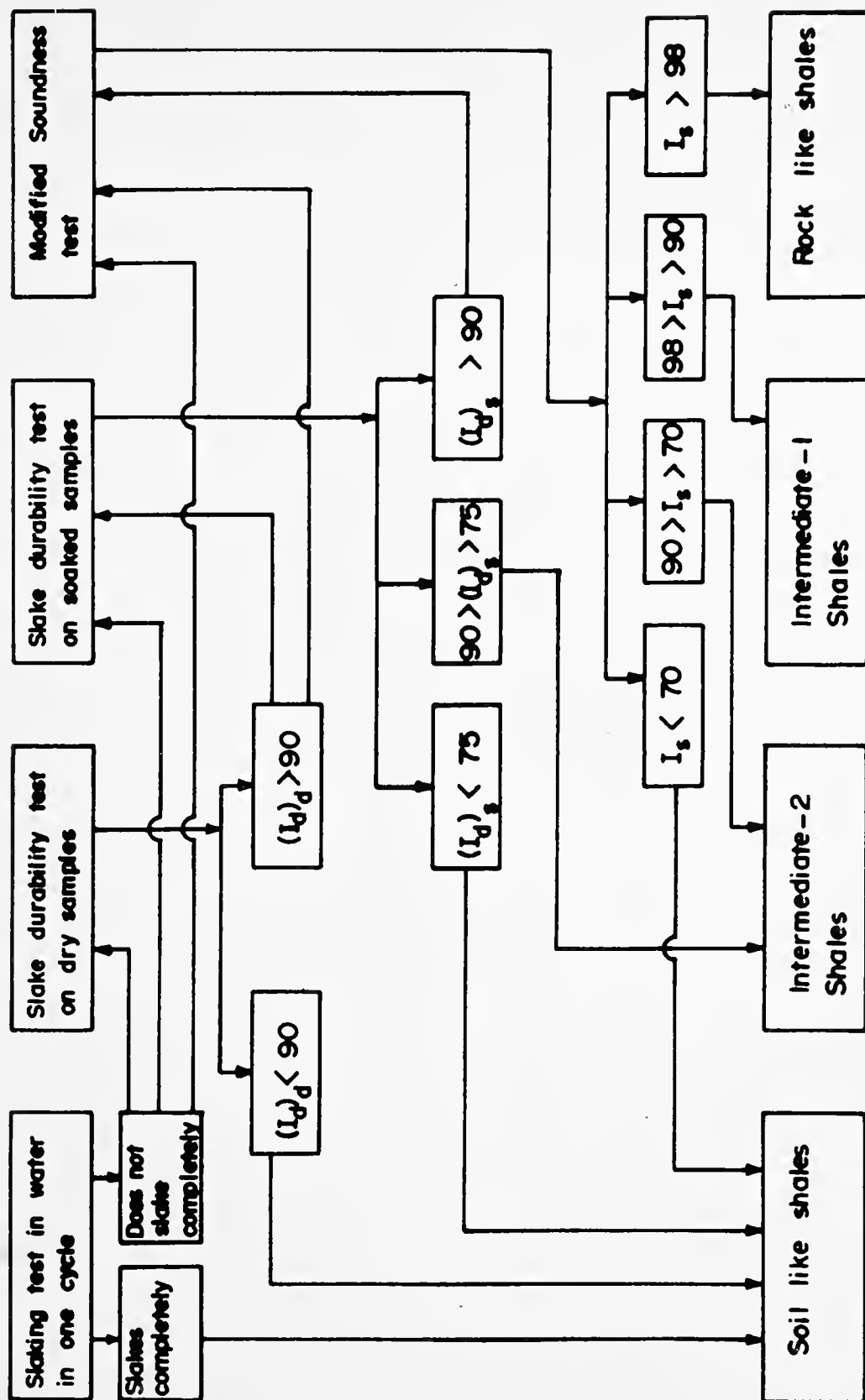


FIGURE 3 - PROPOSED CLASSIFICATION OF SHALES FOR EMBANKMENT CONSTRUCTION.

For the different groups of shales, the following construction practices are suggested by the authors. (These opinions were derived intuitively on the basis of observations in the midwest, but without any actual field tests.)

1. If the material is Soil like, it should be thoroughly broken down before use, and thinner lifts than normally specified for soil may be needed. Expansive characteristics for the shale should also be determined. (Axial swell in the CBR test is a good descriptor.) If the shale powder shows more swelling than that of ordinary clays, it should be accorded the special treatment given an expansive soil embankment, including an effective encasement of non-shale material.

2. For Intermediate-1 and Intermediate-2 shales, specifications should generally vary between those for soil and those for rock fills. Bigger chunks can be used. In Intermediate-2 shales, it is probably necessary to have better density control and to employ an encasement.

3. A mixture of durable and non-durable material should not be used in an embankment, e.g., never mix a Rock like with Intermediate-2. The two materials will degrade quite differently in service, causing potentially major problems. Only top quality Intermediate-1 or Rock like shales should be mixed with limestone or sandstone.

4. If it is not possible to separate good and bad shales, then the whole material should be treated like soil, i.e., be thoroughly broken down.

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APPENDIX A

TEST PROCEDURES

Test for Slaking in Water in One Cycle of Wetting and Drying

A broken piece of shale, roughly equidimensional in shape and weighing between 50 and 60 gm, was oven dried at a temperature between 105° and 110°C for at least 8 hours. The shale piece was allowed to cool for 30 minutes at room temperature, followed by immersion so that it was at least $1/2$ in. below the water surface.

After immersion, the shale piece was observed continuously during the first hour; after that, the condition of the piece was checked at two, four, eight, twelve, and twenty-four hours. The condition of the piece was recorded as: "complete breakdown", "partial breakdown", or "no change". If the piece seemed intact, the cloudiness of the water was also noted. For any shale which slaked completely or partially, the test was repeated to verify the first result.

Figures 4 and 5 show the extremes of material response in the test.

Test for Slaking in Water with Five Cycles of Wetting and Drying

This test was first suggested by Philbrick (11) to separate "compaction" and "cemented" shales.

A roughly equidimensional broken piece of shale weighing between 50 and 60 gm was oven dried at a temperature between 105° and 110°C for at least 8 hours. After cooling for 30 minutes at



**FIGURE 4. CANNELTON SHALE AFTER 15 MINUTES
OF IMMERSION IN WATER.**



FIGURE 5. PAOLI 3 SHALE AFTER 24 HOURS OF IMMERSION IN WATER.

room temperature, the piece was immersed at least 1/2 in. below the water level.

After 16 hours, the shale piece was removed from the water, drained for 10 minutes, and dried at between 105° and 110°C for 8 hours. Five cycles of wetting and drying were repeated, and the condition of the sample was observed at the end of each cycle, and at the conclusion of the test.

Slake Durability Test

The slaking tests discussed above produce rather qualitative results.¹ The slake durability test, on the other hand, measures a weight loss in water which can be expressed as a durability number (N_d). The durability number values vary not only with the type of shale, but, unfortunately, also with such test details as the initial moisture conditions of the shale charge and the testing time (drum revolutions).

The apparatus was developed by Franklin and others at Imperial College London in 1970 (5). The test procedure was further developed and modified to suit Indiana shales.

The apparatus, shown in Figure 6, consists of a drum of 2 mm mesh, 10 cm in length and 14 cm in diameter. Both ends of the cylinder are solid and incorporate suitable driving dogs. One side plate has a quick release mechanism, to permit easy placement and removal of the shale samples.

A motor drive unit attached to the drum revolves it at a speed of 20 rpm in a water trough. The test drum is supported on water lubricated

1. Weight-slaked measurements are possible, but not usual.



FIGURE 6. SLAKE DURABILITY APPARATUS.

bearings, allowing 4 cm unobstructed clearance below the drum. The trough water level is 2 cm below the axis of the drum.

A sample of ten representative shale pieces, each weighing 50 to 60 gm, was oven dried and placed in the test drum. The drum was rotated, and material detached from the pieces passed through the mesh, i.e., became a sample weight loss.

The durability number (N_d) was calculated as the percentage ratio of final to initial dry sample weights,

$$N_d = \frac{B-C}{A-C} 100 \text{ where}$$

N_d = Durability number for a shale for a given number of drum revolutions and given initial condition of shale (oven-dried or soaked).

A = Weight of drum plus dry sample before test.

B = Weight of drum plus dry sample retained after test.

C = Weight of clean and dry drum.

As suggested above, the test was conducted not only on oven-dried samples, but also on samples which were immersed in water (soaked) for six hours before testing. Dry sample weights were used in all calculations.

To determine a suitable value for the standard number of revolutions, preliminary tests were conducted on selected samples for 100, 200, 500 and 1000 revolutions of the drum. The weight loss through the meshed drum increases with the number of revolutions, except that at a higher number of revolutions, viz., 1000, the results were not always reproducible. Five hundred revolutions seems a

reasonable compromise, since it produced both a wide range of durability numbers among the shales and reproducible results for a given shale.

The durability number for 500 revolutions was redefined as the durability index (I_d). Durability indexes both for dry samples, $(I_d)_d$, and for soaked samples, $(I_d)_s$, were determined. At least two tests were run for each combination of variables. The values reported are averages. The lower I_d values indicate a less durable shale. Soaked values $(I_d)_s$ were always lower than the dry ones $(I_d)_d$.

Modified Soundness Test

This test measures the degradation of shales when subjected to five cycles of alternate wetting and drying in a sodium sulfate solution. It is more severe than the previously mentioned slaking tests, and is more effective in distinguishing among the harder and more durable shales.

The test was modified from ASTM C 88-63, Sodium Sulfate Soundness Test (3), which is used to determine the resistance of mineral aggregates to disintegration by a saturated sodium sulfate or magnesium sulfate solution. The standard test proved to be too severe for shales, and after a series of trials, the solution was reduced to 50% saturation.

The charge of shale fragments was 1000 gm, of which 330 gm was between 1/2 in. and 3/8 in., and 670 gm was between 3/4 in. and 1/2 in. Pieces in this size range were roughly equidimensional. Larger pieces tended to be plate shaped, due to the laminated nature of the rock.

(Definition of size by a sieving process of course becomes more arbitrary as the pieces depart from a bulky shape.) The sample was washed with water, and oven dried at 105° to 110°C before weighing.

A saturated solution of anhydrous granular sodium sulfate was prepared in accordance with ASTM C 88-63 procedures (3). The solution was diluted to 50% saturation by adding an equal volume of water. The solution was prepared at least 24 hours in advance of the start of test.

The sample was immersed in the sodium sulfate solution for not less than 16 hours and not more than 18 hours. The solution covered the shale chunks to a depth of at least $1/2$ in. The immersion was conducted at a room temperature of $72^{\circ} \pm 2^{\circ}\text{F}$. The sample was removed from the solution, drained for 15 minutes, placed in the drying oven at 105° to 110°C , and dried to constant weight. After the sample had cooled to room temperature, the process was repeated.

Upon completion of five cycles of immersion and drying, the sample was washed with water until free of sodium sulfate, as determined by the reaction of the wash water with barium chloride (BaCl_2). It was then dried and fractioned on a $5/16$ in. sieve. The weight retained on the sieve was determined. Each test was repeated at least once, and average values were reported.

The Soundness Index, I_s , was defined as the percent retained by weight on the $5/16$ in. sieve. Durability is considered to increase with an increase in the value of I_s .

Compaction and Load-Deformation Tests

These tests were conducted in 6 in. diameter CBR molds. The tests were performed at the 4 compaction effort levels listed below.

i) Standard effort: 5.5 lb rammer with 12 in. fall, 3 layers, 56 uniformly distributed blows per layer;

ii) 0.5 Standard effort: same as above, but 38 uniformly distributed blows per layer;

iii) 1.8 Standard effort: same as above, but 100 uniformly distributed blows per layer;

iv) 4.5 Standard effort: 10 lb. rammer with 18 in. fall, 5 layers, 56 uniformly distributed blows per layer.

For every test the following information was obtained:

- a) Compaction effort,
- b) Molding water content,
- c) Dry density as compacted,
- d) Swell,
- e) CBR as compacted,
- f) CBR soaked,
- g) Ratio of CBR soaked and CBR as compacted.

Breaking Characteristics Test

The breaking characteristics may be the most descriptive feature for shales. They can be thus classified as massive, flaky-fissile and flaggy-fissile. Fissility is associated with a parallel arrangement of particulate units and non-fissility with a random arrangement (9). The

nature of cementing agents is also an important factor that influences fissility.

Massive rocks have no preferred directions of cleaving and breaking, and most of the fragments are blocky. Flaggy rocks will split into fragments of varying thickness, but have a width and length many times greater than the thickness, and with two essentially flat sides approximately parallel. Flaky shales split along irregular surfaces parallel to the bedding and into uneven flakes, thin chips, and wedge-like fragments whose length seldom exceeds three inches. The three breaking types are shown in Figures 7, 8 and 9.

Shales and other soft rocks actually combine varying amounts of massiveness, flagginess and flakiness, which can be represented by points on a triangular diagram.¹

Shales were broken by a hammer, with a large area of contact, or by striking two pieces of shale together. About 1,000 gm of shale were broken in this way, applying approximately the same breaking effort to each batch of shale. Shale pieces with massive, flaggy and flaky characteristics were separated and weighed. Proportions of the three different breaking types were determined to the nearest 10 percent by weight.

1. Much in the same manner as for a soil texture diagram for sand, silt and clay sizes.



FIGURE 7. MASSIVE BREAKING TYPE.



FIGURE 8. FLAGGY BREAKING TYPE.



FIGURE 9. FLAKY BREAKING TYPE.



